Detecting Storm-Generated Suspended Materials in Lake Michigan using ADCP Echo Intensities

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Abstract—Data from Acoustic Doppler Current Profilers deployed in the nearshore region of southeastern Lake Michigan provide evidence of sediment resuspension episodes and cross-shelf flux of materials during strong winter storms. Significant increases (+20 dB) in echo intensity and current velocities correlate well with satellite imagery of a sediment-laden plume transporting material in a cyclonic flow around the lake basinís perimeter. A decrease in echo intensity to near-background levels following resuspension events suggests that the larger particles settle out, leaving the very fine material that remains visible in satellite imagery for many days. Although there were no concurrent Total Suspended Material measurements during the event, the ADCP results suggest that resuspension events and plume movements can be detected.

I. Introduction

In the Great Lakes, as well as in the coastal ocean, the gradients of many biogeochemically important materials are considerably higher in the offshore direction than in the longshore direction. In the presence of these large gradients, cross-isobath circulation is a primary mechanism for the exchange of material between nearshore and offshore waters and is one scientific focus of the NSF/NOAA Episodic Events—Great Lakes Experiment (EEGLE) initiative. Both the alongshore and cross-isobath components of the current exhibit strong episodic behavior due to wind forcing. As opposed to alongshore transport, the advective and diffusive mechanisms driving cross-shore transport and the time scales over which they operate have not been as extensively studied and are not well understood.

Satellite imagery has documented recurrent episodes of cross-isobath transport in the southern basin of Lake Michigan. A 10 km wide plume of resuspended material extending over 100 km along the southern shore of the lake was first observed in satellite imagery by [1], and has since been observed every spring since 1992. The plume often veers offshore along the eastern shore of the lake, close to the location of the areas of highest measured long-term sediment accumulation in the lake [2, 3, 4]. The offshore structure of the turbidity plume often resembles the structure of cold water filaments seen in thermal imagery of the California Current [5]. During the winter, the lakes are usually vertically well mixed from top to bottom at temperatures near or below the temperature of maximum density. Because of their mid-latitude position, the Great Lakes are subject to periodic extratropical storms, particularly during the spring and fall periods when the jet stream crosses these latitudes. Typical intervals between storms are 5-7 days during winter and 7-10 days during summer. Storms rapidly generate strong currents which decay with time scales of several days. Wind-driven transport from episodic atmospheric forcing is a permanent feature of circulation in the lakes. The streamlines of the flow field form two counter-rotating closed gyres [6], a cyclonic gyre to the right of the wind and an anticyclonic gyre to the left (in the Northern Hemisphere). In this classic two gyre pattern, there are two points along the shoreline where cross isobath transport occurs, one on the upwind shore where diverging longshore currents are accompanied by onshore flow, and one on the downwind shore where converging longshore currents are accompanied by offshore flow. As the wind relaxes, the two-cell streamline pattern rotates cyclonically within the basin with a characteristic period corresponding to the lowest mode vorticity wave of the basin [6]. For Lake Michigan, this period is on the order of 3-5 days, closely corresponding to the periodicity of storm forcing.

The EEGLE study site and mooring locations (Fig. 1) were designed to identify the physical processes generating the nearshore-offshore transport of water and suspended materials due to episodic events, and in particular, the coupling of a storm generated coastal turbidity plume and a two-gyre vorticity wave in southern Lake Michigan. The plume contains a substantial

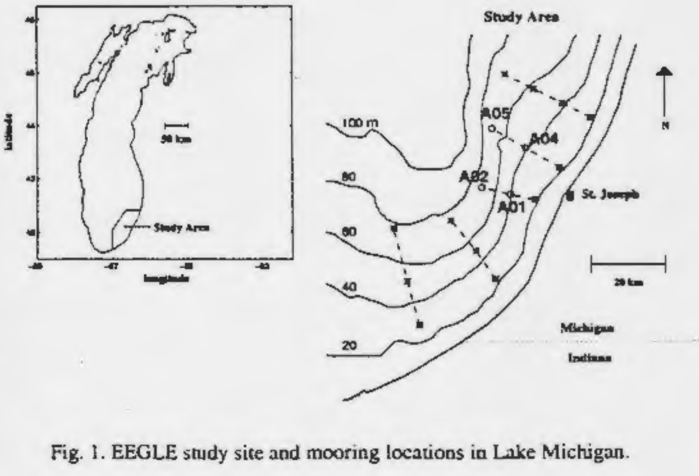

Fig. 1. EEGLE study site and mooring locations in Lake Michigan.

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fraction of the estimated annual load of material to the southern basin of Lake Michigan [2, 7] and the offshore transport region conforms to the area of sediment accumulation. In the fall of 1997, four moorings were placed in this area (Fig. 1). Two ADCP moorings were deployed along the 20 m isobath and two moorings along the 40 m isobath (for convenience, referred to as inshore and offshore, respectively). Table 1 gives the setup parameters for the array of three 300kHz WorkHorse Acoustic Doppler Current Profilers (ADCPs) and one 600 kHz Narrowband ADCP.

TABLE 1

Moorings	A2, A4	A1	A5
Water Depth	20 m	40 m	40 m
ADCP	300 kHz	300 kHz	600 kHz
No. cells	14	33	32
Cell size	1 m	1 m	1 m
# pings	240	240	1600
Std deviation	0.5 cms^{-1}	0.5 cms^{-1}	1 cms^{-1}
Sampling interval	30 min	30 min	30 min
ADCP Depth	17.8 m	37.8 m	37.8 m

In addition to measuring current velocity profiles, ADCPs also record the profile of the backscatter or echo intensity returned from scatterers in the water. The received backscattered signal is a relative measure and is a function of size and concentration of the suspended material. Initially intended for use as a data quality parameter, relationships between sediment and biomass concentrations and echo intensity data have been explored in several studies [8, 9, 10]. A sidebar of the EEGLE current measurement program was to determine if a 300 kHz ADCP would detect the plume. From previous reports [8,11], we were confident that the 600 kHz ADCP could detect the clay to fine sand particles that constitute the plume but not as confident that the 300 kHz profiler would also. If the plume is detectable then, by correlating with traditional method measurements, it may be possible to estimate Total Suspended Material (TSM) concentrations, and characterize the spatial and temporal development and decay of the plume. These estimates would provide validation of sediment transport models currently being developed. Satellite images are limited to cloudless days and near-surface sediment concentrations; hence, imagery of the generation and progression of the plume during the development phase is usually not available.

II. Results and Discussion

February and the first week in March, 1998, were relatively quiet on Lake Michigan with the exception of a 12-hour episode of >10 ms^{-1} northerly winds in mid-February. This quiesent period allowed representative winter background TSM values to be obtained using traditional sampling methods during the first mid-winter EEGLE ship cruise. TSM data collected on a transect near the ADCP moorings in early February varied from 1.4 mg/L in 15 m water depth to 0.8 mg/L in 40 m water [12]. The peak mass distribution of particle sizes in the coastal region was between 20 and 40 µm. Current velocities during the survey were <15 cms^{-1} and echo intensities averaged about 45 dB for the 300 kHz ADCPs.

Four storm events passed over the lake during 9-22 March 1998. Northwesterly winds of 22 ms^{-1}, gusting to 33 ms^{-1}, on 9-10 March generated one of the largest plume events to date (Fig. 2). The plume extended over 300 km of coastline around the southern basin of Lake Michigan. Estimated concentration values above 30 mg/l within the 30 meter contour [13]. Weaker storms with northwesterly winds followed on March 12th and 14th, and northerly winds on march 21st. The NOAA-14 AVHRR visible satellite images starting 12 March, two days after the major storm, show the progression and extent of the plume (Fig. 3). Echo intensities and current velocity components for 8-13 March from mooring A01 (Fig. 4) and A02 (Fig. 5) illustrate the inshore and offshore response to this episodic forcing. Current velocities in the figures have been rotated to yield the alongshore and cross-isobath components relative to the local bathymetry. The isobaths are oriented NNE-SSW so the convention is that the U-component is negative toward the offshore direction and a negative V-component is toward the southerly direction. Maximum northwesterly winds were recorded between 1500 and 1900 LT on March 9, which corresponds to the maximum echo intensity at all moorings. Current magnitudes also peaked with the wind at the nearshore moorings and an offshore component persisted at all stations. Currents reversed with the weakening of the wind during March 10.

To facilitate a comparison of echo intensity data from all four moorings, the echo intensities were vertically averaged and the 14-day mean intensities during the quiet February period were subtracted to normalize values (Fig. 6). The plot shows

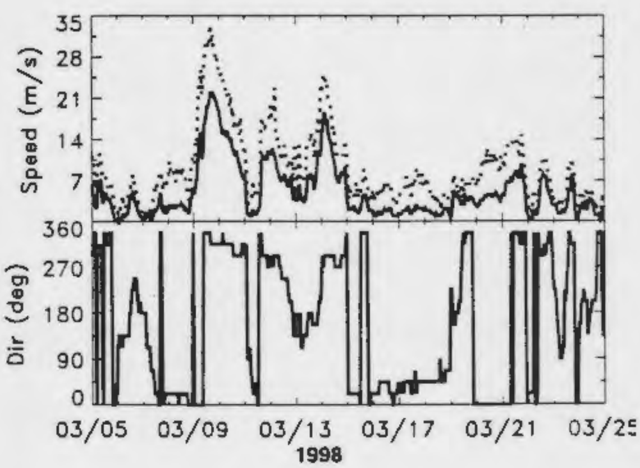

Fig. 2. Hourly wind speed (solid), maximum speed (dotted), and direction recorded at the St. Joseph Water Plant, St. Joseph, Michigan.

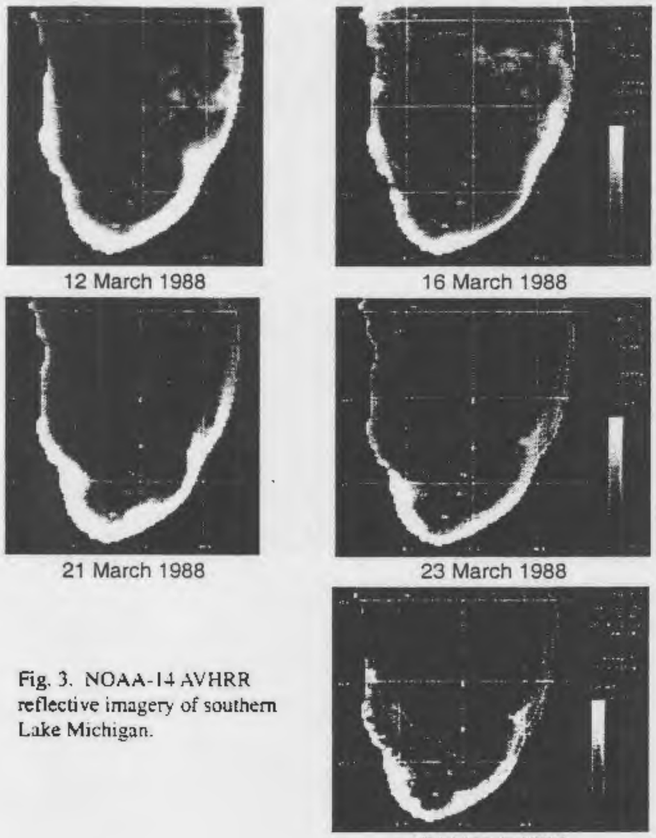

Fig. 3. NOAA-14 AVHRR reflective imagery of southern Lake Michigan.

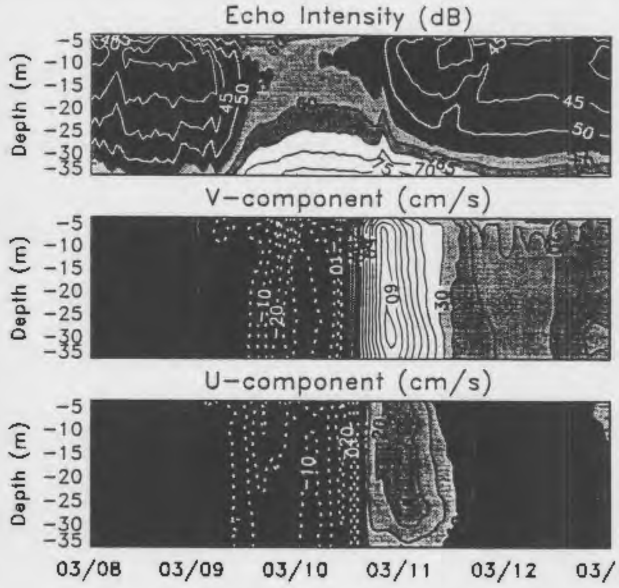

Fig. 5. Mooring A02 echo innsities and current components 8-13 March 1998. Same conventions as Fig. 4.

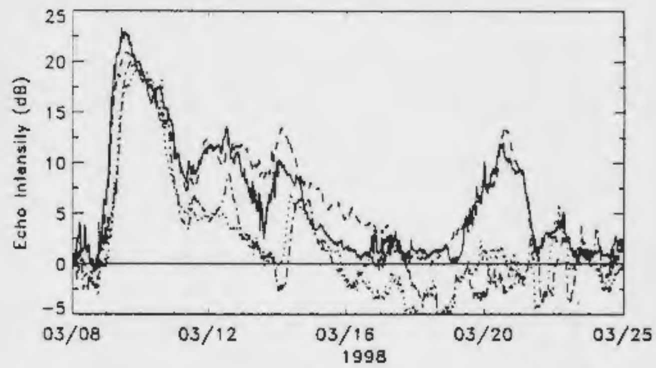

Fig. 6. Vertically integrated echo intensities fromthe four ADCP mooring, 8-24 March 1998. Curves denote the deviations from their respective background means (15-28 February). Solid and dashed curves depict the 20-m moorings (A01 and A04, respectively) and the dotted and chain-dot curves depict the 40-m moorings (A02 and A05, respectively).

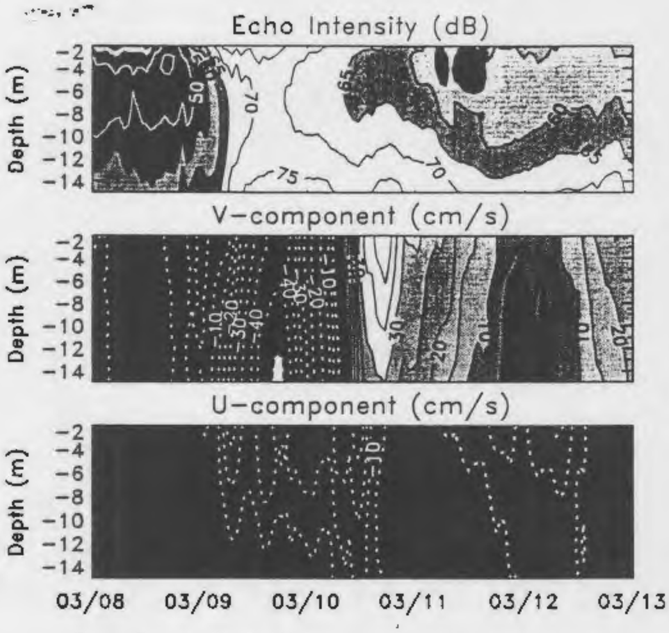

Fig. 4. Mooring A01 echo intensities and current components 8-13 March 1998. Current components are rotated to align with local isobaths. Solid contours denote along-isobath flow int he 'uplake' direction (v-component) and cross-isobath flow inthe 'onshore' direction (u-component).

that the rapid increase in backscatter at the offshore moorings lagged the inshore moorings by about 6 hours. Peak values were nearly equal at 20 dB above their respective means. Echo intensities from the two 40 m offshore moorings decreased to near background levels four days later. The return to background backscattered levels soon after the event suggests that the larger material settles out leaving smaller (<10 μm) reflective particles in suspension that is tracked by satellite imagery from many days.

Backscatter from the March 12th and 14th events, though less intense, followed a similar progression, except the lag between inshore and offshore was longer, about 18 hours, and the plume did not always reach offshore to the 40 m isobath. On the 16 March survey cruise, after three storms had passed, TSM values had increased to 33 mg/L at the 10 m station, 13 mg/L at 30 m, and 1.8 mg/L at the 45 m depth. Winds on March 21st were more northerly at 10 ms^{-1}. The echo intensity at the inshore moorings increased 15 dB but the plume did not extend to the 40 m isobath. The 21st satellite image verifies that the plume was narrower and had less reflectance than on the 12th. Another potential use of echo intensity measurements is for the study of plankton concentrations and variability. Vertical migrations of mesophelagic organisms occur throughout the waters of the world. Reference [10] were the first to report a diurnal pattern in the backscattered signals measured by an upward-looking 150 kHz ADCP in the high speed Somali Current during a seven month deployment. Reference [9], correlating the backscattered acoustic signals with zooplankton samples collected with a net, concluded that it is possible to predict zooplankton biomass to about (15 mg m^{-3} but only after careful calibration of the traducers and electronics. Diel vertical migrations (DVM) in Lake Michigan are evident from the consistent echo intensity fluctuations at the 40 m mooring sites during mid-winter (Fig. 7). Echo intensities increased sharply by 6 to 7 dB starting at the end of astronomical twilight (~1.5 hours after sunset) and decreased to daylight values at sunrise. The dominant zooplankters in Lake Michigan that exhibit DVM are *Mysis relicta, Diaptomus, and Limnocalanus*. It is notable that after the March 9 storm, DVM was not observed again until late April. In situ zooplankton sampling using net tows and optical particle counter are planned during the next field season to better understand the echo intensity, zooplankton concentration relationship.

The measurements described above were obtained during the pilot year of the EEGLE project. The ADCPs have demonstrated that suspended materials are trackable during the episodic storm events and may be a useful technique for obtaining temporal and spatial TSM. The purposes of the pilot year ship cruises were to test equipment and methods and to obtain background data. No attempt was made to sample during extreme

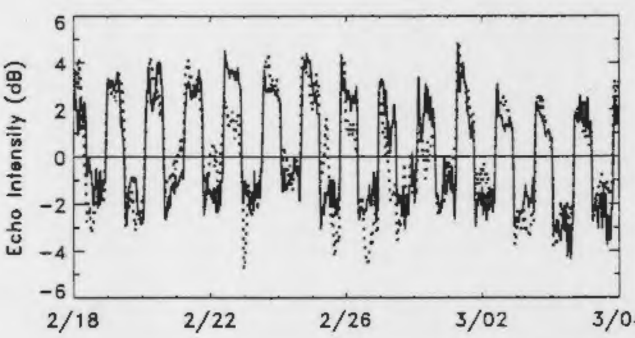

Figure 7. Echo intensity variations showing the diel vertical migration of zooplankton at the 4-m moorings A02 (dotted line) and A05 (solid).

events. Field measurements of TSM and material properties are necessary before any quantitative echo intensity-TSM correlation can be attempted. Arrays of ADCPs with several frequencies have been deployed and shipboard data collections of necessary materials data will be done during the upcoming 1998-99 winter/spring season.

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